Monitoring Wadden Sea subsidence by GPS

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Introduction

To keep subsidence cause by mineral extraction within accepted limits it is - in the Netherlands - continuously monitored by GPS stations. This article extends the analysis of (Houtenbos, 2011) and describes the results after ten years of monitoring subsidence due to gas extraction from three field clusters.

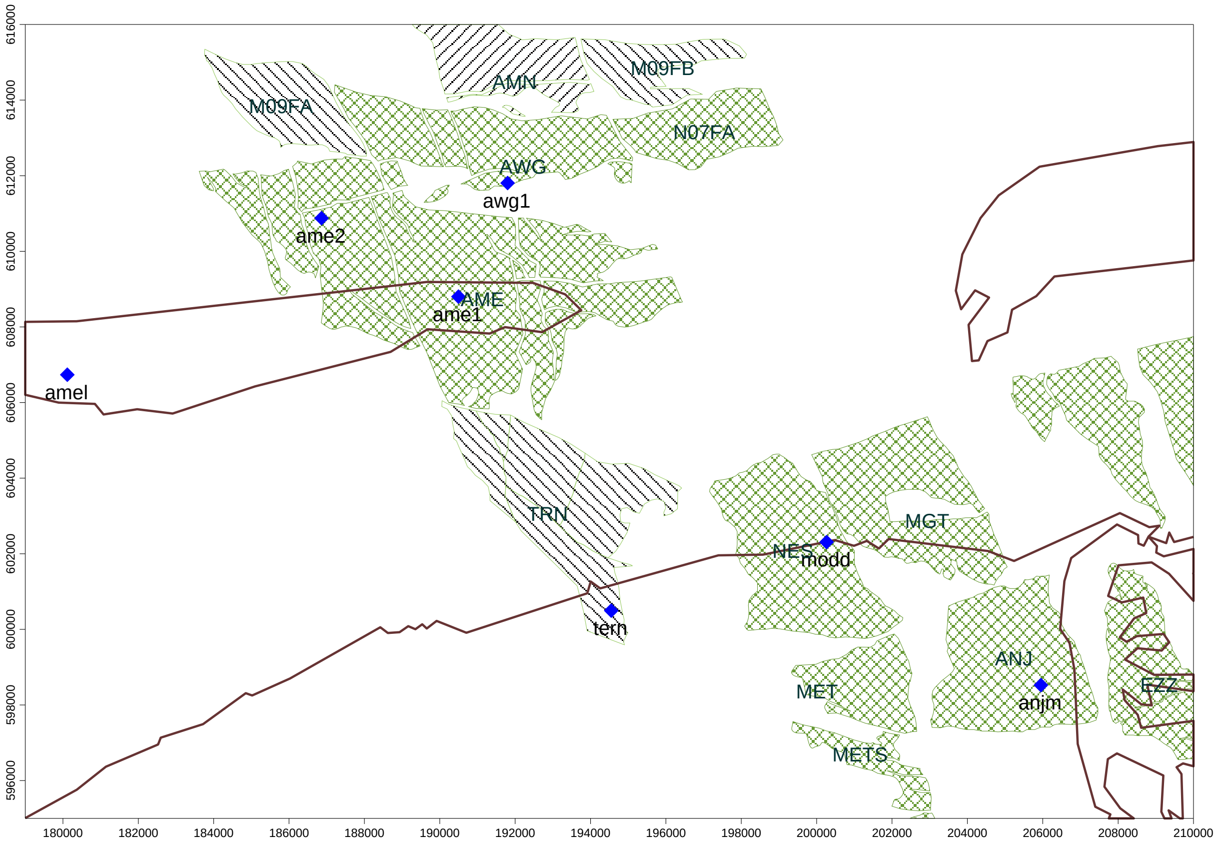


Figure 1: Monitored area. GPS station in blue diamonds, producing gas field in dark green, non-producing fields in light green, topography brown. Timeseries for GPS stations ame2 and awg1 not yet made available.

GPS Station	AME1	MODD	ANJM
Gasfield 1	Ameland-Oost > 1986	Nes > 2007	Anjum > 1997
Gasfield 2	Ameland-Westgat > 1993	Moddergat > 2007	Metslawier > 1997
Gasfield 3	N07-FA >2011		Ezumazijl > 1999
Start extraction	01-01-1986	01-02-2007	01-08-1997
Start GPS	25-05-2006	15-12-2006	01-06-2006
End GPS	29-04-2017	29-04-2017	29-04-2017

Table 1: Primary GPS time series

Apart from the 3 GPS stations listed above, shorter time series were available for the stations AMEL and TERN. The first is located near the benchmark, that served as the reference point for all previous the levelling surveys over the subsidence area, the second on a gas field, planned to go in production shortly.

Processing

The dataset comprises hourly latitude, longitude and height positions of the GPS antennas with respect to a set of presumably stable reference stations. Monthly production data per gas field from January 2003 allows investigation of the relation between antenna displacement and gas extraction.

GPS measured latitude, longitude and heights are converted to national RD/NAP x, y and z values. Spikes, steps, high frequency noise, daily and yearly variations are removed.

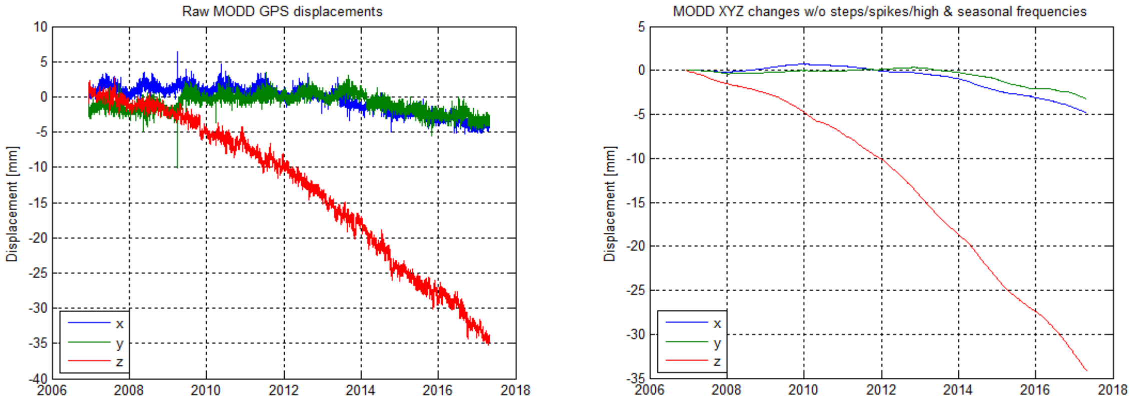


Figure 2: Raw and processed version of the Modd x-, y- and z-displacement.

Finally, vertical and horizontal displacement rates and the bearing on the horizontal displacement is computed at monthly intervals for comparison with monthly production rates.

Results

The time series for AMEL and TERN were too short and/or too far away from the subsidence bowls to allow analysis of all aspects. Figure 4 does however reveal some peculiar aspects of these time series.

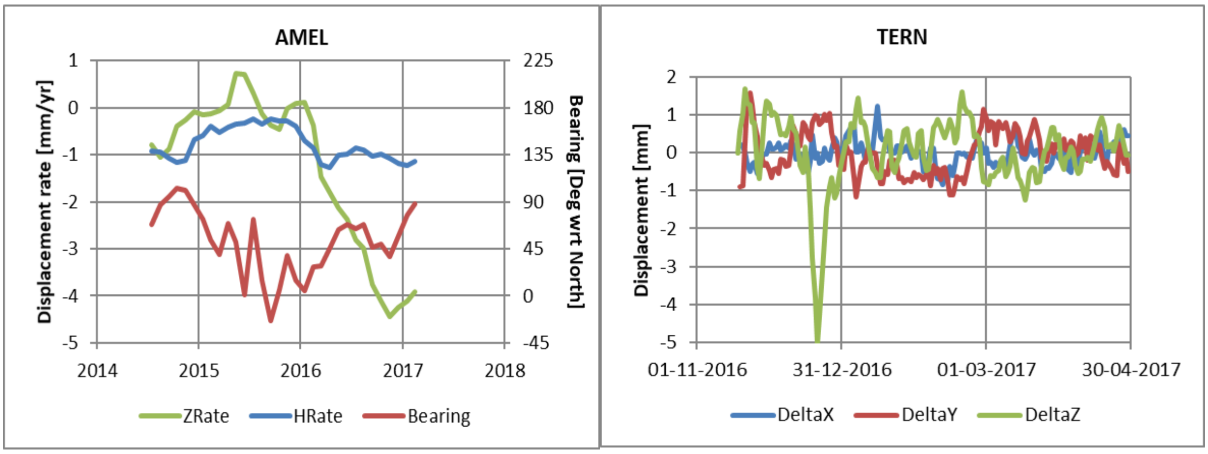


Figure 3: Displacement rates and bearing of station AMEL and displacements of station TERN.

The ‘amel’ GPS station is part of the national AGRS network, on which all official positioning in the Netherlands is based. The station is located on the Rijkswaterstaat building at the Ballumerweg, Nes, Ameland, near underground height marker 000A2592, which in turn has served as the presumed stable reference point for all subsidence levelling surveys on the island. The GPS timeseries indicate the vertical displacement rate increasing from 0 to 4 mm/year in the last year recorded. In the same period, the horizontal displacement rate increased to 1 mm year in the direction of the Ameland gas fields.

The time series for the ‘tern’ GPS station shows a symmetrical dip of 5 mm over 2-week period. It is not clear what the cause (instrumental artefact, elastic displacement of the antenna w.r.t. surrounding area or displacement of the antenna with the elastically subsiding surrounding area) has been nor what the reaction of inspectors would/should have been, if such an anomaly occurred on a producing gas field.

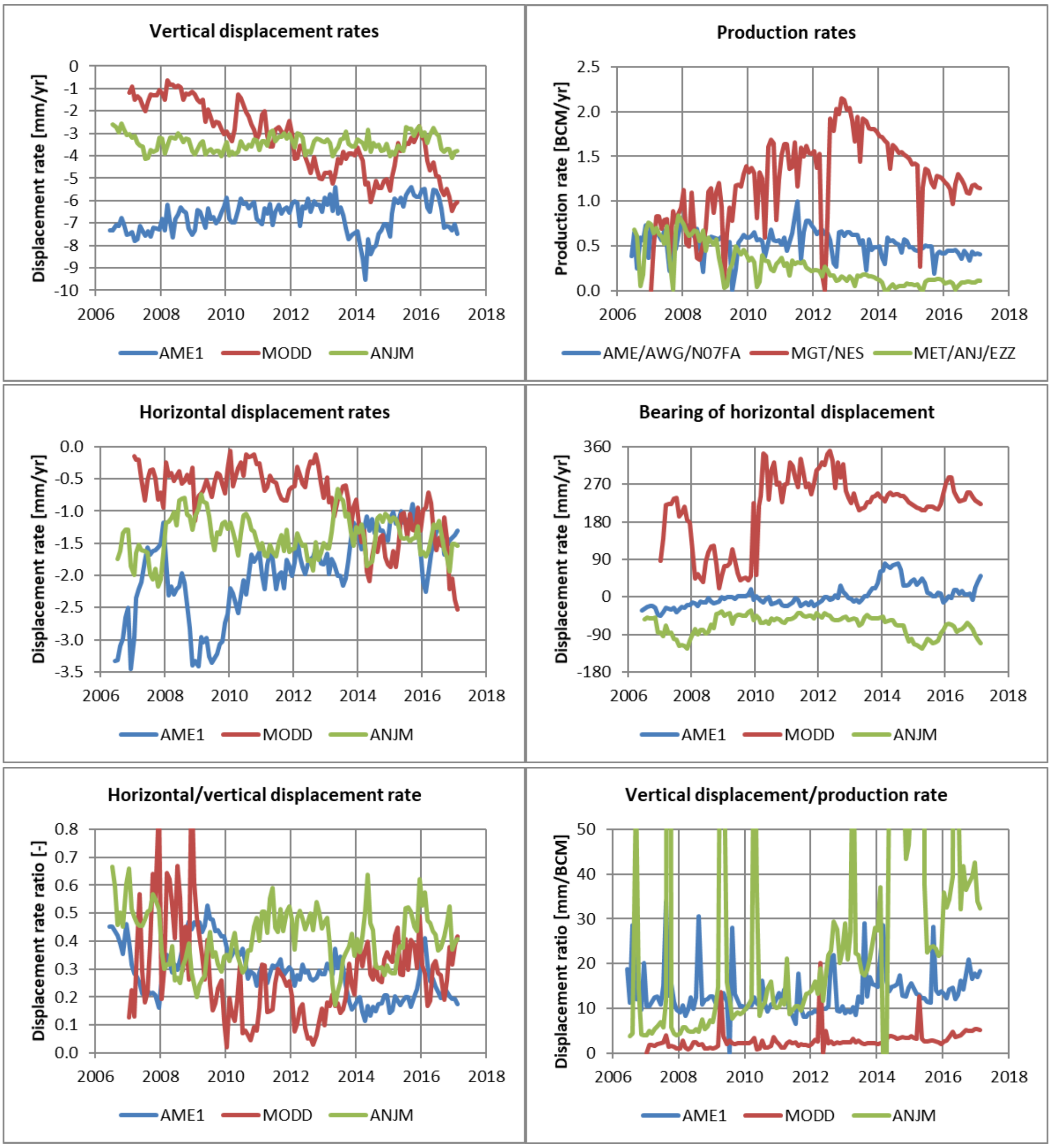


Figure 4: Results of the 3 primary GPS stations. From upper left to bottom right: vertical displacement rate, production rate, horizontal displacement rate, bearing of the horizontal displacement, ratio between horizontal and vertical displacement and finally ratio between production and vertical displacement rate.

Over the past 5 years subsidence per billion cubic meters (BCM) produced gas doubled over the Ameland field cluster and roughly tripled over the Moddergat/Nes and Metslawier/Anjum/Ezumazijl clusters.

GPS Station	AME1	AMEL	MODD	ANJM
Vertical rate [mm/yr]	7.2	4.0	6.2	4.0
Horizontal rate [mm/yr]	1.4	1.2	2.4	1.5
Direction hor.displ. [deg]	0	80	230	100
Production rate {BCM/yr]	0.42	0.42	1.17	0.10
Hor./vert.displ. ratio [-]	0.19	0.30	0.39	0.38
Vert./prod.rate ratio [mm/BCM]	17.1	-	5.3	40.0

Table 2: Displacement characteristics at the end of the monitoring period early 2017.

GPS measures the instantaneous 3D displacement of its antenna, not the maximum horizontal and vertical displacement rates. The relation between the rates measured at the GPS location and the maximum rates can be described by the following equations:

$$\dot{z}(x,y,t) = \dot{z}_{max}(t).e^{-½r^{\delta}}$$

$$\dot{h}(x,y,t) = \dot{h}_{max}(t).\left(\frac{\delta.e}{2(\delta-1)}\right)^{(\delta-1)/\delta} r^{\delta}.e^{-½r^{\delta}}$$

$$r^2 = \left(\frac{(x-x_{mid}).sin\alpha + (y-y_{mid}).cos}{a}\right)^2 + \left(\frac{(x-x_{mid}).cos\alpha - (y-y_{mid}).sin\alpha}{b}\right)^2$$

in which x_{mid}, y_{mid}, a, b and α are the x and y- coordinates of the centre, the semi-major, semi-minor axis and the bearing respectively of the contour at 60% ($e^{-1/2}$) of maximum subsidence, δ the flattening of the subsidence bowl, and $\dot{z}$ and $\dot{h}$ the vertical and horizontal displacement rates. The maximum horizontal rate is reached at:

$$r = \left(\frac{2(\delta-1)}{\delta}\right)^{1/\delta}$$

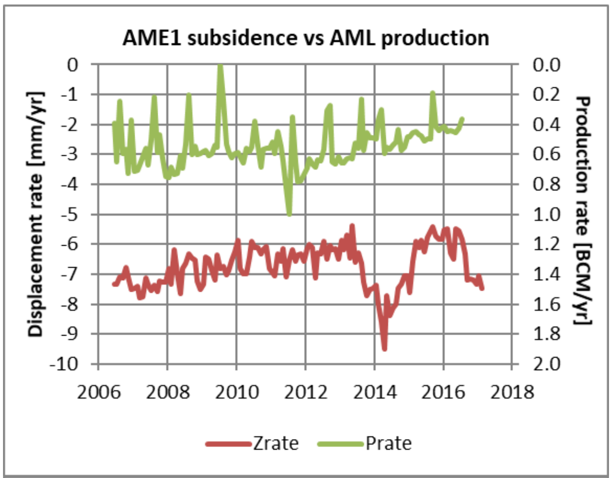
which for a typical δ value of 2 equates to the 60%-z_{max}-contour above the edge of the reservoir. This horizontal displacement is of particular importance for the derivation of subsidence from InSar as it distorts the relation between measured line of sight displacement and the vertical displacement sought.

GPS Station / Field Cluster	AME1/AML	MODD/MGN	ANJM/MAE
Maximum vertical rate [mm/yr]	7.8	6.7	4.3
Maximum horizontal rate [mm/yr]	1.9	3.3	2.9

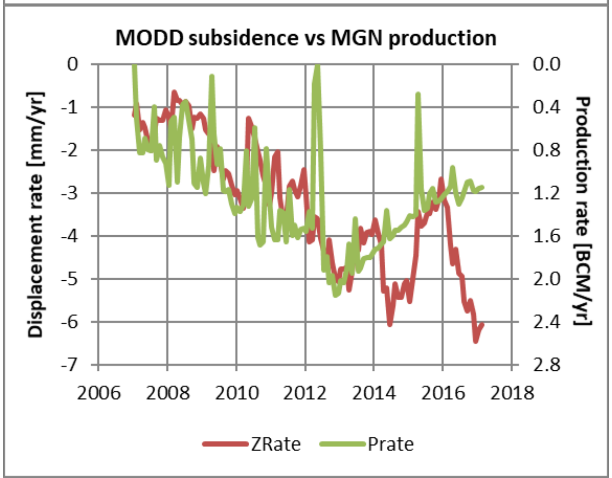
Table 3: Implied maximum displacement of the AME/AWG/N07FA, MGT/NES en MET/ANJ/EZZ field clusters.

Interpretation

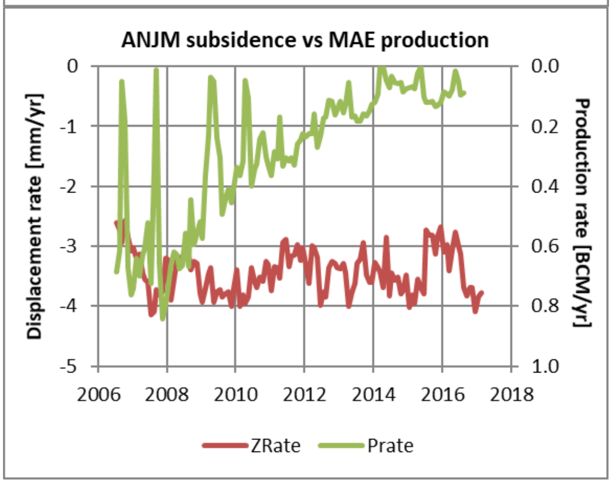
The relation between subsidence at the GPS location and production is complex. The contribution of a specific production volume to measured subsidence decreases with the distance of the specific block from which the volume is produced to the GPS station. Even at constant overall production rates measured GPS displacement will therefore vary with the instantaneous geographical distribution of producing wells.



While total AME/AWG/N07-FA production rates halved from 2011 to 2017, the subsidence rate at the GPS station increased from 6.4 to 7.2 mm per year. While the centre of gravity of production shifted towards N07-FA in 2011, it appeared too far away and too early to explain the subsidence rate peaking in 2014.



Just prior to the 2007 start of production from the MGT/NES fields the MODD GPS station subsided already 1 mm per year. This may have been caused by production from the nearby MET/ANJ/EZZ fields. It does however complicate the translation of GPS results into action to control subsidence due to further production. From 2012 production rates dropped 40%, while subsidence rates increased 20%, demonstrating that reducing production is incapable of stopping subsidence acceleration, let alone decelerate subsidence over periods of 5 years.



Decimation of the production rate from the MET/ANJ/EZZ cluster over the last 10 years had no effect on associated subsidence rates.

Discussion

The prime concern in Wadden Sea area is the conservation of ecological values. Initial subsidence predictions assumed pressure depletion and compaction in the gas bearing portions of the reservoir rock only. Under this assumption, the reduction of pressure divided by the gas expansion factor is proportional to production volumes. There is growing evidence that pressure depletion and compaction extents to aquifers beneath and around producing gas fields.

- (NAM, 2017) reports: “Note that the AWG-110 well found the Ameland-N07FA reservoir depleted by some 60 bar compared to the N07-2 discovery well. As the only 2 producing fields in the vicinity are Ameland-Oost and Ameland-Westgat, it is likely that the Ameland-

N07FA structure is connected to either one of them. There is 1 production well drilled into Ameland-N07FA field: AWG-110." The pressure development in the various compartments of the fields suggest pressure communication between AME and N07FA via AWG. This implies pressure communication across faults with throws larger than reservoir thickness, through gas/water contacts and through the lateral aquifer between AWG and AME. As similar conditions prevail all around the Ameland fields, pressure communication between gas and water bearing portions of the reservoir is likely all around Ameland (see Figure 5).

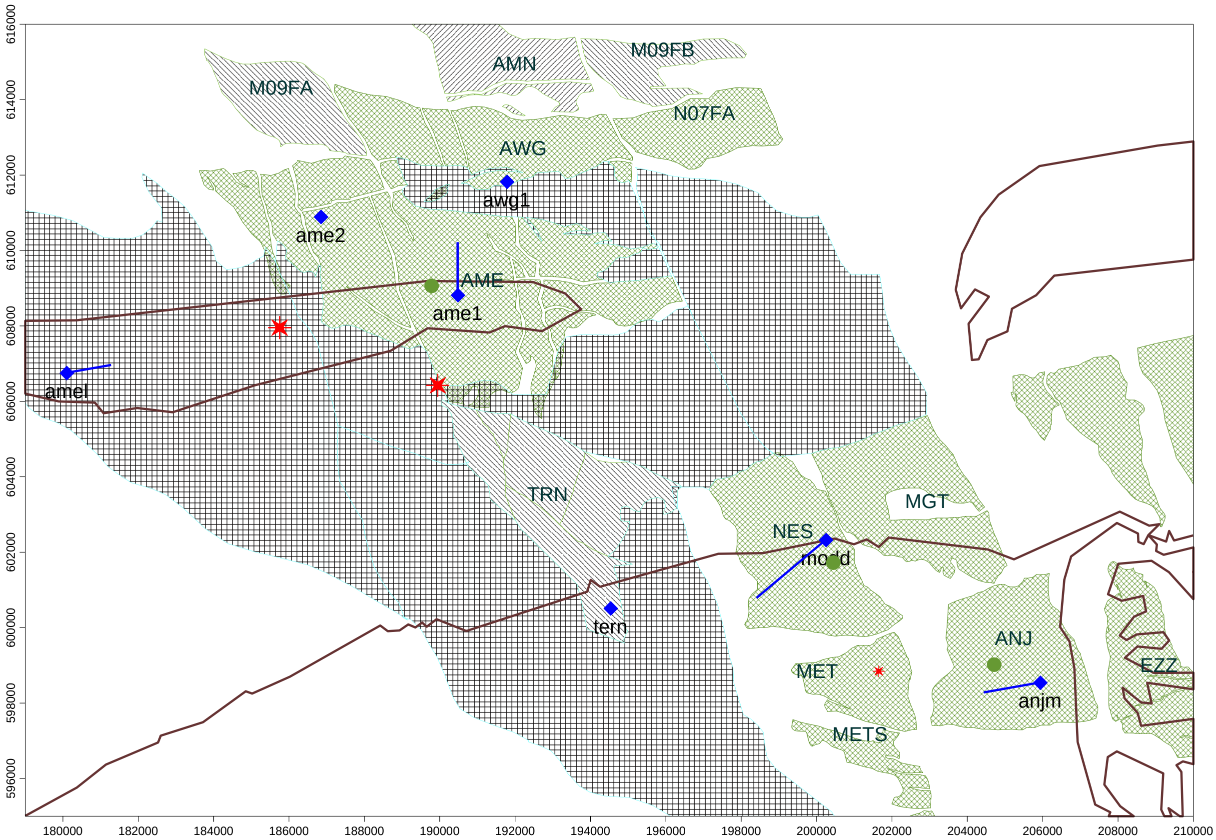


Figure 5: Subsidence area with previously determined, cumulative bowl centres as green dots, 2017 instantaneous horizontal displacement rate vectors in dark blue, aquifers in light blue and earthquake locations as red stars.

- KNMI reports 2 induced earthquakes of magnitude 1.8, one in 2005 and one in 2013, near faults between gas and water bearing reservoir compartments. The driving mechanism is worrisome, as reactivation of normal faults implies more compaction on the water bearing than on the gas bearing side of these faults.
- The magnitude and direction of horizontal and vertical displacements of GPS station 'amel' (see Figure 3 and Figure 5) suggest a subsidence sink, such as the aquifer, nearby.

Currently, an exponentially decaying compaction response to pressure depletion is the prevailing explanation for the observed lagging of subsidence behind production. The explanation is undercut by more recent observations:

- The time decay constant, needed to bring modelled subsidence in agreement with measured subsidence, is not constant but lengthens as production progresses.
- Subsidence, reservoir pressure and balance of produced and injected gas volumes vary in perfect synchrony without delay through injection/production cycles in the Norg underground gas storage facility.

It would appear that the time lag between production and subsidence is not to be found in the relation between pressure depletion and compaction, but in the relation between pressure depletion in gas and water bearing portions of the reservoir. Significant differences in permeability and viscosity cause a far slower propagation of pressure waves in water bearing than in a gas bearing reservoir rock.

Under the assumption of a time decay function governing compaction of gas bearing rock only the compaction and subsidence volume increase asymptotically to the limit of uniaxial compaction coefficient times reservoir thickness times gas bearing area times the pressure depletion: $V_{subs} = V_{comp} = c_m.h.A_{gas}.\Delta P$. Under the assumption of a direct compaction response to pressure depletion and sluggish pressure communication between gas and water bearing portions of the reservoir the ultimate volume limit will be: $V_{subs} = V_{comp.gas} + V_{comp.water} = c_m.h.(A_{gas}+A_{water}).\Delta P$. In the Ameland case the subsidence volume may be up to 4 times larger than due to depletion of gas bearing reservoir alone, be it that it is likely to take much longer before pressure is evened out over the entire gas en water bearing reservoir.

Conclusions

1. Over the last 5 years subsidence per cubic meter produced gas increased by a factor 2 to 3.
2. Major reduction of production rates failed to slow down subsidence above the Metslawier/Anjum/Ezumazijl gas fields. 40% reduction of the production rate from Subsidence above the Moddergat/Nes fields even continued to accelerating despite slowing down production by 40%.

Recommendations

1. Focus on subsidence volume rather than subsidence in the deepest point of the bowl. Derive and compare separate fully continuous spatio-temporal subsidence models from geodetic and geomechanical input, interpolating between discreet data points, based on the covariance of respectively geodetic and geomechanical input.
2. Improve verification of aquifer depletion models. Monitor development of pressure and depth of gas-water-contacts in aquifer penetrating wells, such as AME-103A. Monitor potential widening of the subsidence bowl due to aquifer depletion by an additional GPS station between 'amel' en 'ame1'.

References

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